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ADVANCES IN AEROSPACE SCIENCES

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ADVANCES IN AIRCRAFT ENGINES SINCE 1903

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Abstract

An attempt has been made in this paper to highlight the evolution in aircraft engines from 1903 in which the Wright brothers had the first successful powered flight with a gasoline engine that produced 12 hp and weighing 152lb (i.e. weighing 12.6 lb per hp developed) to the experimental stage scramjet and hypersonic combustion engines. The earliest aero engines were piston engines based on auto cycle stationary, either radial in design or in line. These were succeeded by the popular rotary engines. Then more sophisticated and powerful stationary in-line engines were used until the arrival of the jet engines. The invention of jet engines by Sir Frank Whittle and Hans J.P. von Ohain revolutionised the powered flight. The basic requirements of a typical aircraft engine are described. Different types of engines, their working principles, advantages, disadvantages, performance, type of aircraft that it can be powered, etc are discussed. The trend in increase in thrust and reduction in the weight of the engines over the years are plotted. It has been found that the weight to thrust ratio of the engines witnessed about 125-fold reduction (12.6 lb/hp in 1903 to 0.10 lb/hp for latest engines). Similarly it was observed that the specific fuel consumption (SFC) also reduced by 67% (1 lb/hour/lbst in early 1900 to 0.33 lb/hour/lbst for the latest engines). Some interesting features in engines like thrust augmentation, thrust reversal, thrust vectoring, noise reduction technologies etc. are described.

Key words: Piston engine; jet engine; specific fuel consumption; specific weight; specific thrust

1. Introduction

Man had always dreamed of flying like birds. Flying requires lifting and propelling the craft forward (propulsion). After several attempts man finally succeeded in lifting the flying vehicle and propelling at modest speeds. The invention of airplane was a fundamental turning point in the history. It redefined the way the wars were fought; revolutionised travel and commerce; fueled the process of technological change; and helped to shape a world in which the very survival of a nation would depend on its scientific and technical prowess. Flight is, and will continue to be, one of humankind's most significant, stunning and magnificent achievement.

Aircraft engines are one of the most complicated engineering systems developed in the world involving various engineering extremities like high temperature, high revolutions per minute (rpm) etc. So a precise research, design and manufacturing system is required to make perfect and highly reliable engines to get the required thrust. Thrust is the force, which moves an aircraft forward through the air, generated by the propulsion system of the aircraft. Different types of engines develop thrust in different ways through some form of application of Newton's third law.

1.1. Early Airplane Engines (Piston Engines)

Initially the first airborne vehicles (gliders, balloons and airships) flew with the winds and later on attempts were made to power them by means of propellers. Literature review shows that for the first time a propeller driven by a 3 horse power (hp) steam engine was employed in 1852 in France and later on a 9hp battery operated electric motor was used for driving the propeller [20].

1.2. *Wright Brother's Engine*

The engine designed and built by Charlie Taylor and the Wright brothers for their Flyer, although much lower powered, had a greater place in history because it propelled the first successful powered flight in 1903. It was a four-cylinder, in-line gasoline engine (Fig.1). It weighed 152 pounds (lb), had a displacement of 200 cubic inches, and produced 12 hp at 1090 rpm. It had no fuel pump, carburetor, or spark plugs [4].

1.3 *Engines after Wright Brothers*

At the start of the twentieth century, aircraft engines were simple, low-powered machines that were designed and built one by one for a specific aircraft. But very soon, engines started being built in quantity, often by several manufacturers in different countries. In the United States, particularly during World War I, automobile manufacturers dominated the aero-engine field until companies that specialised in aircraft engines were established in the 1920s [13]. There were tremendous advances in aircraft reciprocating engines from the beginning of controlled powered flight in 1903 to the end of World War II. Engine power and reliability increased dramatically, while the important parameter weight-to-power ratio fell steadily. Developments in engine design made so far have resulted in continuous improvement in efficiencies and fuel economy in modern engines.

The earliest aero engines were stationary either radial in design or in line. An Anzani engine carried Louis Bleriot's monoplane across the English Channel in 1909. It was a three-cylinder, air-cooled, semi-radial engine that developed 25 hp. The most commonly used radial engine was 50hp Antoinette (Fig.2) designed and built by Lon Levavasseur (France) in 1910. It was safe, strong, and fairly powerful. Its weight-to-power ratio (2.2 lb/hp) was not surpassed for next 25 years. These were succeeded by the popular rotary engines in which the radially disposed cylinders rotate around an axis. This gave better cooling of the engine and hence gave more power and also had improved reliability. The Australian Lawrence Hargrave built a three-cylinder rotary engine in 1889. The best known rotary engines were the 50 hp Gnome (Fig.3) and Le Rhone, which were used on the majority of aircraft (during World war I) until the in-line Liberty engines, designed for mass production, started dominating the aero-engine market. Thereafter more sophisticated and powerful stationary in-line engines were developed until the arrival of the jet engine [18].

America's most significant contribution to the World War I effort was the Liberty. The Liberty 400 hp V-12, air-cooled engine, was one of the war's most powerful engines and one of the workhorses of the war. The Liberty became the standard wartime aircraft engine, which was produced by Packard, Lincoln, Ford, and General Motors etc. More than 13,000 engines came off the assembly line before the Armistice, and more than 20,000 were built by the time wartime production ended early in 1919 [14]. Table-1 shows some of the major piston engines developed and the weight to power ratio reduction over the years.

1.4 *Superchargers*

Superchargers are devices used in reciprocating engines to deliver additional air to the engine. They draw power from the engine and compress the air before it flows to the cylinders by using a small rotary compressor powered by gears in the engine's crankshaft. Superchargers are important at high altitudes where air has low density and pressure due to which the engine performance deteriorates. But the reduction gears make the engine bigger, heavier, and complex. Lee Chadwick of Pottstown (Pennsylvania) built a supercharged Vanderbilt Cup racer in 1908. [3].

1.5 Turbochargers

A turbocharger (Fig. 4) also called 'turbosupercharger' is a supercharger that is driven by a turbine. The turbine draws power from the engine exhaust. Using a turbine to power supercharger is more efficient since they uses exhaust gas pressure. Turbochargers can provide more "supercharging" than the gear-driven type of supercharger. In 1916 a French inventor, Auguste Rateau, designed the first turbocharger for fighter aircrafts at high altitude.

1.6 Compound Engine

In a compound engine, exhaust gases from piston motor drives a turbine. The turbine then delivers extra power to drive the propeller. This arrangement boosts the overall efficiency and permits longer range. In 1950s The C version of 'Super Constellation' L-1049 was the first commercial aircraft certified with a turbo-compound engine.

2. Jet Propulsion

The limitations of the propeller driven by piston engines were realized due to a drop in efficiency of the propeller at high speeds due to the onset of compressibility effects. Air races could be consider as one of the motivation to go for more powerful and efficient propulsive systems. The squid fish which employed hydraulic jet propulsion can be considered as the first ever jet propulsion device that existed in the world. The first effort to employ jet propulsion by man goes back to Hero's reaction turbine in Egypt called the "aeolipile" (Fig.5) developed in 100BC. In 1687 Sir Isaac Newton attempted to put his newly formulated laws of motion to the test with his "steam wagon" as shown in Fig.6 [14, 20]. This may be considered as a precursor to the later developments employing the reaction of a steamjet to drive a carriage and the golden age of jet engines.

Sir Frank Whittle of England was totally fascinated by the challenges of high speed flight. He graduated from the Royal Air Force College in 1928 and his thesis discussed gas turbines and jet propulsion. In a 1930 patent application, he outlined the concept of the modern turbojet engine. Delayed by funding difficulties, he got a test model running in April 12,1937. The first successful flight of the engine (W1) designed by him powered the Pioneer aircraft developed by the Gloster Company in May 15, 1941. The General Electric company was given the contract to manufacture the American version of 'W1'.

As a young doctoral student in Physics at Gttingen University, Hans J.P. Von Ohain of Germany, totally unaware of Whittle's work, arrived at a similar solution: that to achieve high speeds, a form of propulsion other than the piston engine and propeller was required. He quickly got commercial backing for his research. By 1937, he successfully tested an engine and first flight engine was the HES 3B, which powered HE178 aircraft and flew on August 27, 1939 [2,7].

After the successful efforts of Whittle and Ohain, different types of jet engines were developed to suit for different categories of aircrafts to achieve required thrust, with better efficiency and fuel economy. A brief description of various types of jet engines is outlined below.

2.1 Turbojet Engine

The turbojet is the basic engine of the jet age. Air is drawn into the engine through the front intake. The compressor squeezes the air to many times that of normal atmospheric pressure and forces it into the combustor. Here, fuel is sprayed into the compressed air, ignited and burned continuously like a blowtorch. The burning gases expand rapidly rearward through the turbine. The turbine extracts energy from the expanding gases to drive the compressor, which intakes more air. After leaving the turbine, the hot gases further expands in the nozzle and exit at the rear of the engine there by giving the aircraft its forward push. The layout of principal components in a typical turbojet engine is shown in Fig.7. Turbojet engines are mainly used in military aircrafts due to lower fuel economy [18, 20].

2.2 The Turboprop Engine

In a turboprop engine commonly called as 'Propfans', (Fig.8) a propeller is mounted in front of the turbine engine. The propeller creates the main thrust from the gas turbine engine. It offered greater speed and power than the piston engines and better fuel economy compared to the turbojet. Gyorgy Jendrassik of Ganz wagon (Hungary) designed the first working turboprop engine, Cs-1' in 1938. This engine was first tested in August 1940; but Cs-1 was abandoned in 1941 without going into production because of War. Max Mueller designed the first turboprop engine that went into production in 1942. Efforts were also made in Junkers Aircraft Company (Germany) with the help of Herbert Wagner, but the turboprop developed by them in 1942 did not enter any flight programme. The first successful aircraft, the Gloster Meteor flew with a turboprop engine in Britain in 1945. The Junkers 022 turboprop was also made in the same year. The turboprop is used for low speed and short-range transportation [2, 3,]

2.3 The Turboshaft Engine

A turboshaft is similar to a turboprop engine, differing primarily in the function of the turbine shaft. Instead of driving a propeller, the turbine shaft is connected to a transmission system that drives helicopter rotor blades, electrical generators, compressors, pumps, and marine propulsion drives.

2.4 The Turbofan Engine

. In a turbofan engine, one or more rows of compressor blades extend beyond the normal blades and results in pulling more air in to the engine compared to a turbojet. Most of this excess air is bypassed around the power section and then out with the exhaust gases. The twin-spool version has two compressors, each driven by its own turbine. Advantages of turbofans are better performance at lower fuel consumption and less noise. Turbofans are mainly used for long range transportation. Boeing 707 first flew in 1952 with a Conway turbofan engine. The first long-range service started with turbofan engines in 1968 with 250 passengers. In the early 1990s, GE developed the GE 90 turbofan engine to power Boeing 777, which produced a world's record thrust of 110,300 lb in ground testing. It has 123 inches diameter fan (world's largest) and highest bypass ratio (9:1) to produce the greatest propulsive efficiency [3,17].

2.5 The Ultra High Bypass Jet Engine

During the 1980s, GE developed the Unducted Fan (UDF) engine, which eliminated the need for a gearbox to drive a large fan. The jet exhaust drives two counter-rotating turbines that are directly coupled to the fan blades. These large span fan blades, made of composite materials, have variable pitch to provide the proper blade angle of attack to meet varying aircraft speed and power requirements. Powerplants such as the UDF engine are capable of reducing specific fuel consumption further 20-30% below current subsonic turbofans [18]. The improvement in fuel efficiency with increasing bypassing is shown in Fig.9.

2.6 The Ramjet Engine

The air rushing towards the inlet of an engine flying at high speeds is partially compressed by the ram effect. If the air speed is high enough, this compression can be sufficient to operate an engine without either compressor or turbine and hence no moving parts. The ramjet (Fig.10) has been called a flying stovepipe, because it is open at both ends and has only fuel injectors in the middle. A ramjet starts operating at speeds above 320 kmph, and they are commonly used for military applications. A vehicle powered by a ramjet must first be accelerated by other means to a sufficiently high speed [18].

2.7 The Scramjet Engine

The Supersonic Combustion Ramjet (Scramjet) engine differs from the ramjet in a way that combustion takes place at supersonic air velocities inside the engine (Fig.11). Though mechanically it is simple, but more complex aero-thermodynamically. Normally the fuel used is hydrogen. The first successful flight test of a Scramjet engine, conducted by University of Queensland, Australia in July 2002 (HyShot programme) achieved a speed of Mach 7.6. Researches are going on to develop the hypersonic combustion engines across the world. The spin-off of supersonic/hypersonic combustion airbreathing engine technologies will help in high-speed air transportation concepts [15,18].

2.8 The Pulse Jet Engine

A pulsejet is similar to a ramjet, except that a series of spring-loaded shutter-type valves is located ahead of the combustion section. In a pulsejet, combustion is intermittent or pulsing rather than continuous. The most widely known pulsejet was the German V-1 missile. A pulsejet engine delivers thrust at zero speed and can be started from rest, but the maximum possible flight speeds are below 960 kmph. Due to poor efficiency, severe vibration, and high noise its use is limited to low-cost, pilot-less vehicles [15].

2.9 Prerequisites of Aircraft Engines

- Lightweight and low frontal area per horsepower produced.
- Low specific fuel consumption.
- Ability to operate in different altitudes and quickly varying ambient conditions.
- High reliability, large time interval between overhaul.
- Easiness of starting and inspection.

2.10 Performance Analysis

It is interesting to see the improvement in some of the important parameters of aero-engines over years.

2.11 Speed and Passenger Capacity

The speed and passenger capacity of an aircraft directly depends on the power of the engine. Due to the advancement in technology, dramatic improvements in engine performance and unit size are evident; engine powers (few lbs to 100,000 lbs), speeds (from 10 kmph to Mach 2.2) and carrying capacity (single/two persons to 555 passengers for latest aircrafts in service) over the years. Fig.12 and Fig.13 shows these improvements in travel time and carrying capacities respectively [1,6].

2.12 Specific Fuel Consumption

Specific Fuel Consumption is a measure of the fuel consumed by an engine. There are two types of specific fuel consumption: i) Thrust Specific Fuel Consumption (TSFC) defined as fuel-flow (FF) rate per pound of thrust produced (FF/Thrust) and ii) Power Specific Fuel Consumption (SFC) defined as fuel-flow rate per hp produced. (FF/hp). As shown in Fig.14, it is observed that the TSFC reduced by 67% (1 lb/hour/lbst in early 1900 to 0.33 lb/hour/lbst for the latest engines) [5, 6].

2.13 Specific Weight

Specific weight is the weight per unit thrust produced by the engine also called weight to power ratio. With the introduction of the jet engines specific weight of the engine reduced substantially. It has been found that the specific weight of the engines witnessed around 125-fold reduction (12.6 lb/hp in 1903 to 0.10 lb/hp in 1990s). The reduction trend in the specific weight over the years is plotted in Fig.15 [5].

2.14 Specific Thrust

Specific thrust is the thrust produced per unit mass flow rate. The term specific thrust simplifies mathematical analysis of jet engine thermodynamics. It gives us an idea to "size" an engine during preliminary analysis. The required value of thrust is determined by the aircraft drag. The ratio of required thrust to specific thrust will tell how much airflow the engine must produce and this determines the physical size of the engine. Specific thrust reduces as bypassing increases. The specific thrust got reduced from 60lbst/lb/s in 1940s to 20lbst/lb/s in 1990s [5, 15].

2.15 Propulsive Efficiency

It is the ratio of propulsive power by rate of production of propulsive kinetic energy. The comparison of propulsive efficiency for different kinds of engines is shown Fig.16. It can be seen that the turboprop is preferable for lower range of speeds (around 280 mph). The performance of turbofans is maximum at around 750mph and that of turbojets continuous to improve with speed [11, 20].

3. Some Interesting Technological Features in Jet Engines

3.1 Thrust Reversing

Although most modern aircraft brakes are sufficient during normal conditions, when runways become icy or snow covered, an additional method of bringing the aircraft to stop is needed. A simple and effective way to reduce the landing distance of an aircraft is to reverse the direction of the exhaust gas stream. Many high by-pass ratio engines reverse thrust by changing the direction of the fan airflow. Ideally, the gas should be directed in a completely forward direction, however this is not possible mainly due to aerodynamic reasons. So usually a discharge angle near to 45 degrees is chosen. There are several methods of obtaining reverse thrust on jet engines: (i) clamshell-type deflector doors to reverse the exhaust gas stream, (ii) target system with external type doors to reverse the exhaust and (iii) fan engines utilize blocker doors to reverse the cold stream airflow. Propeller-powered aircraft reverses the thrust by changing the pitch of the propeller blades.

3.2 Thrust Vectoring

Thrust Vectoring is the procedure that makes the exhaust nozzle structure turn to make forward, vertical or side-to-side thrust. Vectoring supplies the directional thrust necessary for vertical take off and landing (VTOL) and short take off and landing (STOL) military aircrafts. Vectoring also gives aircraft a better rate of climb, increased control during flight and more maneuverability. In most cases special nozzles can be moved in flight to change the direction of the thrust, allowing rapid changes in the pitch of the aircraft. The most successful design is the engine which powers the Harrier, the Rolls-Royce Pegasus. Harrier has four smaller nozzles, two on each side. These nozzles can swivel more than 90, from facing directly backwards to straight down, and even slightly forwards, meaning the Harrier can fly backwards very slowly.

3.3 *Thrust Augmentation*

Thrust augmentation is the increase of thrust for a short period for specific functions such as when aircraft take off from short runways, and in combat, where a rapid increase in thrust may occasionally be required. The military engines augment thrust by using afterburners. Fuel injectors are added between the turbine and the nozzle, which injects fuel to mix and burn with the excess oxygen. The energy added by the afterburner is transferred as kinetic energy through the nozzle resulting in an increase in thrust with less fuel efficiency. In commercial aircrafts the engines augments thrust by injecting water or methanol to the exhaust gases there by increasing mass flow rate and hence the thrust [1].

3.4 *Noise Reduction Technology*

Even though some piston-engine planes produced noise that found annoying, the arrival of jet engines increased the level of noise on many aircraft. The first attempts to reduce aircraft noise according to Federal Aviation Administration (FAA) regulations were made in the 1950s. Major source of jet engine noise came from the region behind the engine where the high-velocity exhaust mixes with the lower velocity surrounding air. In Europe, nozzles with corrugated outer edge were designed for better mixing of the high-velocity efflux with the air behind the engine. In USA, designers used this method and another one involving venting the exhaust through several tubes. But both of these methods increased the drag and reduced the engine performance, the multi-tube approach increased weight substantially. Another solution emerged in the 1960s was the "ejector-suppressor." This was essentially a large tube with noise absorption lining fitted aft of the engine around the exhaust nozzle that allowed air from outside the engine to mix with the exhaust, reducing the final efflux velocity. But work on fully lined ejector-suppressors was halted, as high-bypass ratio turbofan engines with reduced noise became available. In a high-bypass turbofan, the central turbine drives a large fan in front of it that passes a lot of air around the turbine and mixing with the hot jet exhaust insulates the engine, acting as a muffler [14].

4. Conclusion

It can be seen that tremendous technological developments and achievements had been occurred in aircraft engines in the past 100 years. The invention and advances of jet engines and the successful test flight of scramjet engine are a few to mention. Since aircraft engine involves various engineering extremities like high temperature, high rpm environments, the achievements in aircraft engine stands for the development in engineering with precision and reliability. Noise remains a major challenge for any future large, fast aircraft so more improvements are necessary in the field of jet accoustics to have quieter aircrafts. The experimental stage Hypersonic Combustion engine technology, an elusive engineering goal for decades could someday allow aircraft to fly above Mach10, a pace now reserved to conventional rockets. Let us hope that the technological advances in the future will render more reliable lightweight engines with more thrust and less fuel consumption.

Acknowledgement

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Table-1 : Weight to Power Ratio Reduction in Piston engines Over the Years (source : [10])

Engine	Year	Design	Coolant	No. of Cylinders	Power (hp)	Weight (lb)	lb/hp
Wright	1903	In-Line	Liquid	4	12	152	12.6
Anzani	1910	Radial	Air	3	30	121	4.0
Gnome	1908	Rotary	Air	7	50	165	3.3
Antoinette	1910	Radial	Liquid	8	50	110	2.2
BentleyBR2	1918	Rotary	Air	9	230	500	2.2
Wright J-5 Whirlwind	1925	Radial	Air	9	220	510	2.3
Rolls-Royce Merlin	1936	"V"	Liquid	12	1030	1320	1.3
Merc-Benz D-B601	1938	"V"	Liquid	12	1360	1540	1.1
Napier Sabre	1940	"V"	Liquid	12	2200	2500	1.1
Allison V-1710	1941	"V"	Liquid	12	1250	1595	1.3
P & W R-4360	1945	Radial	Air	28	3000	3600	1.2
Contential O-200	1959	Opposed	Air	4	100	188	1.9
Lycoming O-540	1959	Opposed	Air	6	250	396	1.6
Lycoming XR-7755	1940s	Radial	Liquid	36	4000	6050	1.5
Lycoming IO-540-K	1960s	Opposed	Air	6	300	443	1.5
Lycoming TIO-540-J	1960s	Opposed	Air	6	350	518	1.5

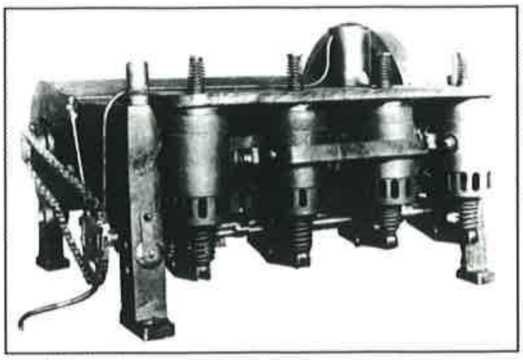

Figure 1. Wright Brothers' Flyer engine

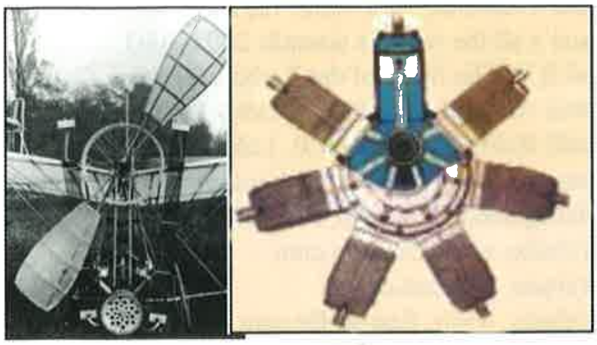

Figure 2. Antoinette radial engine

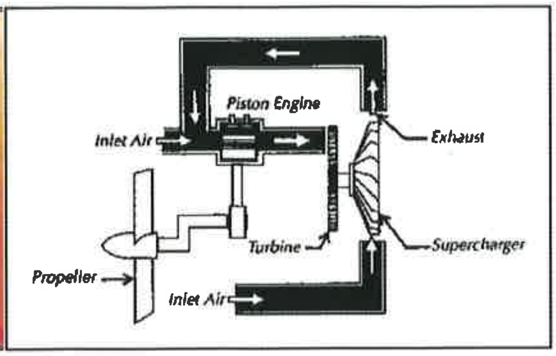

Figure 3. Gnome rotary engine

Figure 4. Piston engine with turbocharger (source: [14])

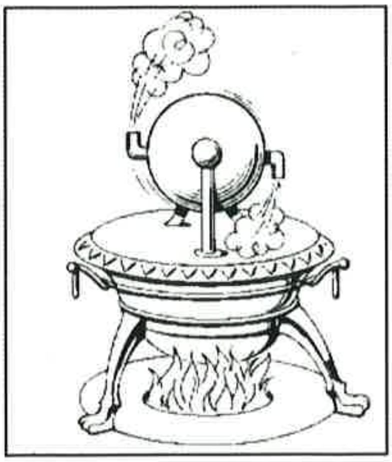

Figure 5. Hero's reaction turbine

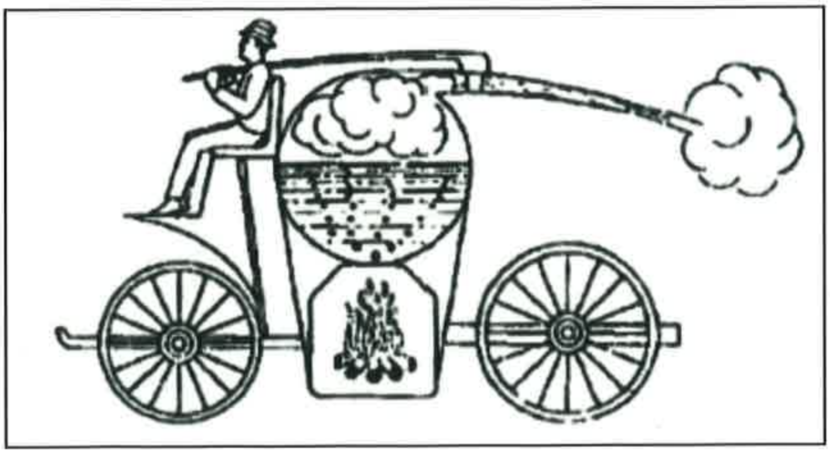

Figure 6. Steamjet driving the wagon (source: [14])

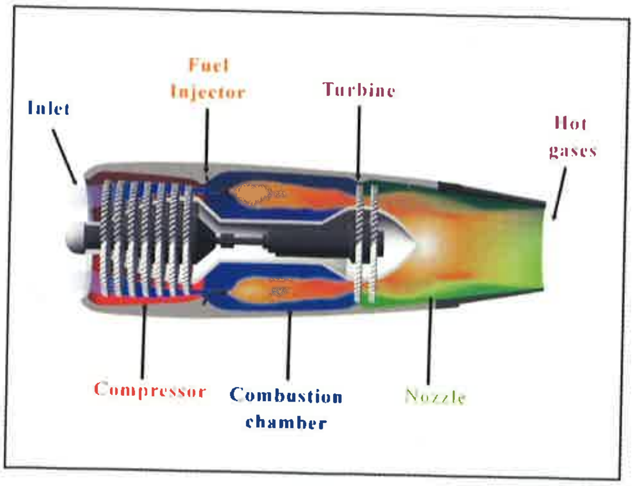

Figure 7. Layout of a turbojet engine

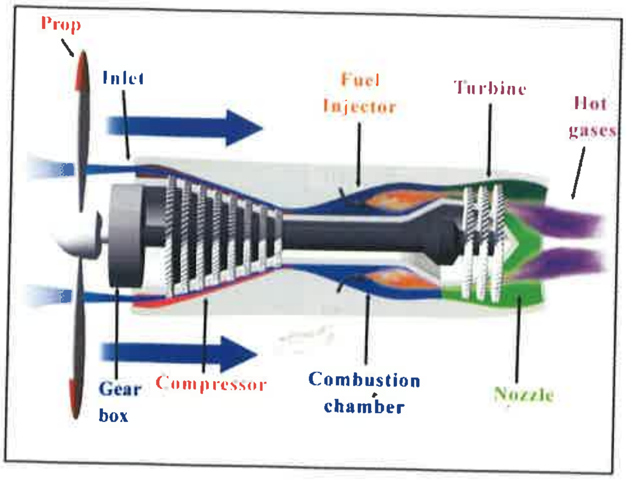

Figure 8. Layout of a turboprop engine

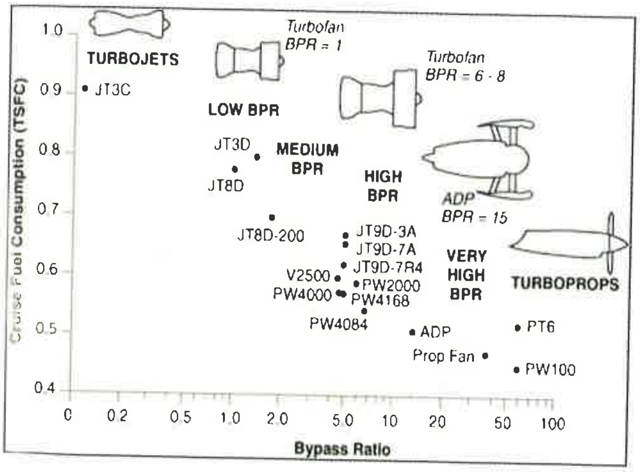

Figure 9. Trend in fuel efficiency with bypass ratio (Source: [11])

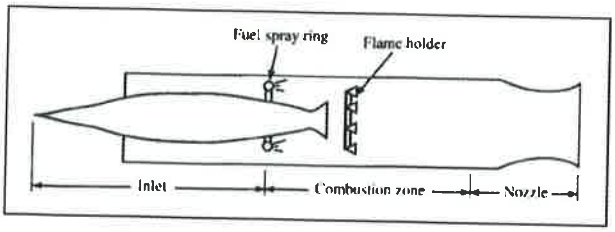

Figure 10. Line diagram of Ramjet engine

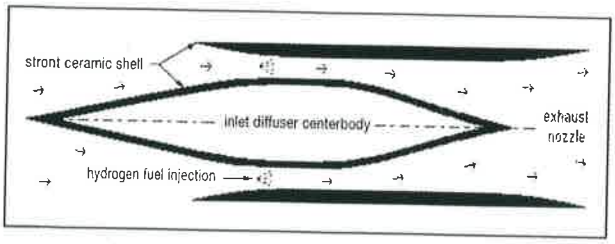

Figure 11. Line diagram of Seramjet engine

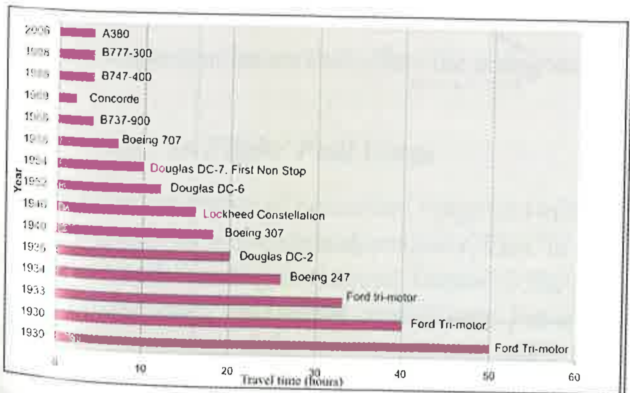

Figure 12. Improvement in travel time (New York to Los Angeles: 3950 km)

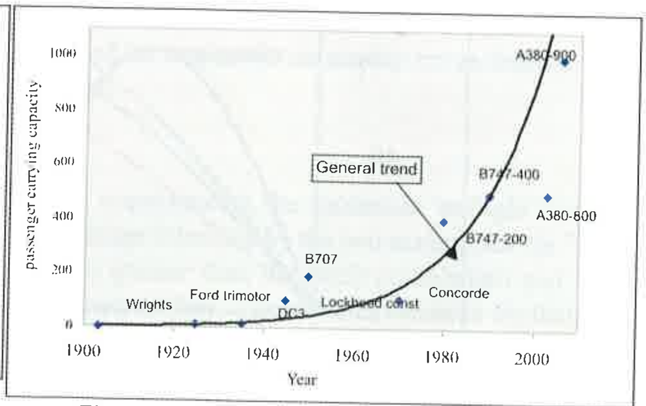

Figure 13. Increase in passenger carrying capacity

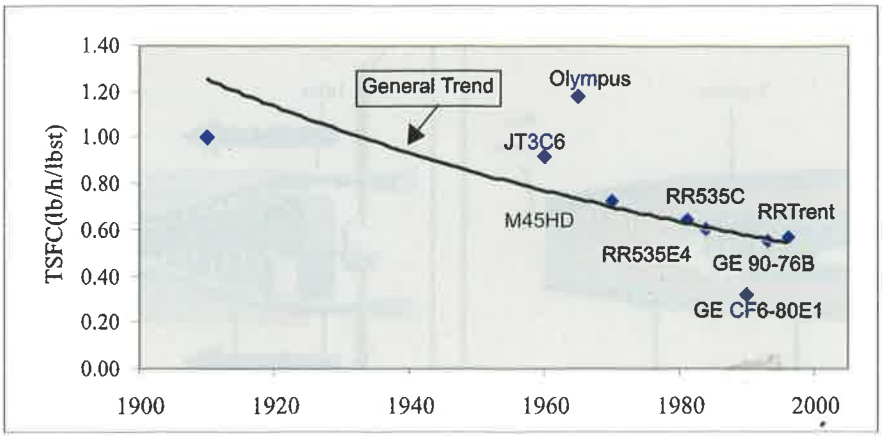

Figure 14: Reduction trend in specific fuel consumption over years

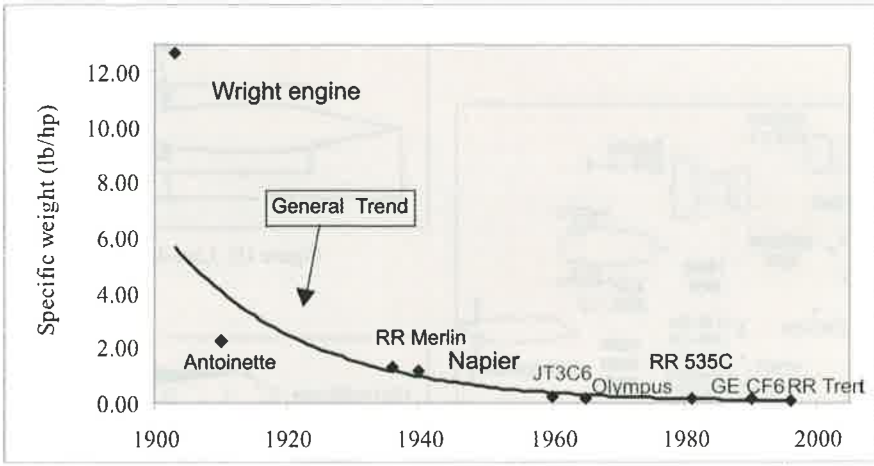

Figure 15: Reduction trend in specific weight (weight to power ratio) over years

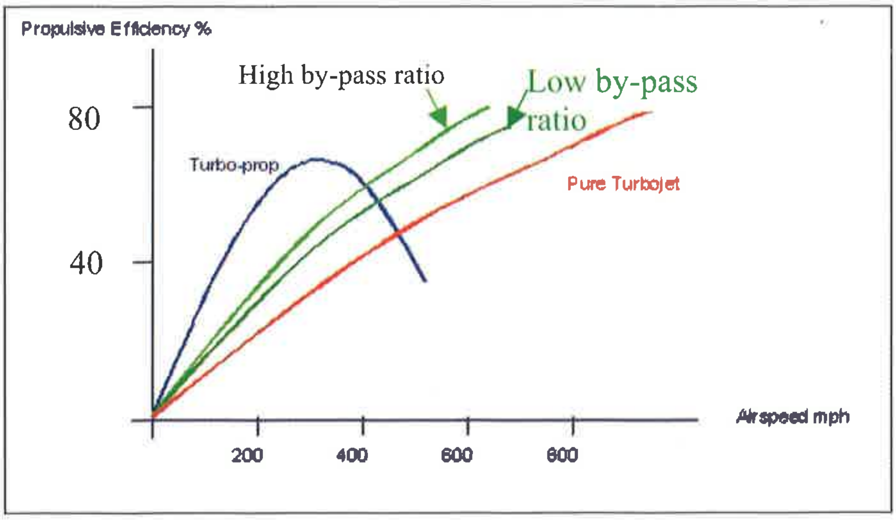

Figure 16: Propulsive efficiency of different types of engines